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# Experimental Investigation on Indicated Pressure and Heat Release for Direct Hydrogen Injection in a Dual Fuel Diesel Engine

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## ABSTRACT

This paper presents the research results for a diesel and hydrogen fueled engine. The research object is a four-cylinder, four-stroke ADCR engine with a displacement of 2,636 cm$^3$. In the experiments, glow plugs were replaced with compressed hydrogen injectors and a special adapter. Hydrogen was supplied directly into a combustion chamber using a test injector. A hydrogen dose in the tests was changed at selected test points and ranged from 0 to 160 dm$^3$/min. The research were conducted at 1,500 rpm. A hydrogen injection start angle and maximum hydrogen dose were specified from the preliminary experiments. The following parameters were analyzed: indicated mean effective pressure, maximum pressure, crank angle of maximum cylinder pressure occurrence and heat release. The obtained results were statistically analyzed. The conducted analysis focused on determining whether there are significant differences between early and late injection and how these changes affect the measured parameters.

**Keywords**: diesel engine, direct hydrogen injection, dual fuel, combustion engine.

## INTRODUCTION

There has been much discussion of the inevitable end of the internal combustion engine, however, this situation is not represented by the number of scientific papers. In the early 21st century, the sciencedirect.com database provided every year a few hundred research articles searched by the keyword of "internal combustion engines". In 2019 and 2020, there were already approx. 4000 publications per year, while in 2021 over 5100 research papers on internal combustion engines were made available. It is noteworthy that these figures refer to more than 2200 articles about hydrogen, published just in 2021 and collected just in this particular database. The use of hydrogen as an alternative fuel in internal combustion engines was often studied in the early 21st century [1-4]. Enthusiasm waned a little bit after several years of intensive funding for hydrogen projects, and car manufacturers focused attention on hybrid solutions but interest in hydrogen and its use as a fuel in internal combustion engines have recently returned [5-8]. The growing problem of global warming and the need to reduce emissions from motor vehicles in any known way are not without significance now [9]. Infrastructure has also been improved, and drivers have looked more favorably on an alternative fuel as hydrogen. Users have become more aware of both ecology and safety of hydrogen installations. However, universal solutions to be launched onto the market, which has become slightly diversified thanks to hybrid drives, still require a lot of research and analysis.

A fuel to power a compression-ignition engine should ensure the entire fuel supply system to function correctly, especially precise elements of high-pressure equipment. A composition of a fuel-air mixture should ensure correct and efficient combustion and make the production of harmful components in a combustion process as little as possible and not be risky to the natural environment. Particulate emissions are especially fundamental in compression-ignition engines [10, 11]. The reduction of particulate matter emission can be achieved by a dual-fuel supply of a compression-ignition engine [12, 13]. However, the use of hydrogen in diesel engines could require some modifications on the engine calibration. Among the different phenomena involved in diesel combustion, autoignition significantly affects the engine efficiency. This work analyzes the autoignition behavior of diesel and biodiesel fuels under a H2-rich ambient. Two different liquid fuel replacements (10% and 20% by energy. However, the use of an additional fuel requires simulation studies [14-16] related to the distribution of this fuel in the combustion chamber and correct mixture formation.

The studies [17] and [18] are especially interesting because they focus on the impact of cylinder pressure on fuel distribution during injection. The correct course of fuel spraying in a combustion chamber is extremely important for an engine to achieve optimal operating parameters and minimize emissions of toxic substances. Injection equipment plays a significant role in the formation of a fuel-air mixture and affects the intensity of fuel outflow from spray holes, the range of the front of a fuel spray and the way fuel droplets are distributed in a combustion chamber [19]which is a crucial aspect for the correct operation of modern DI Diesel engines as it greatly influences the combustion process and the exhaust emissions. A complete understanding of spray impingement is quite complex. A mixed numerical-experimental approach is proposed in this paper. The experimental tests are carried out with a high pressure (up to 120 MPa. Recording images inside a cylinder of an internal combustion engine can be difficult mainly due to high temperature and pressure, limited access to a cylinder and a very dynamic nature of recorded phenomena [20]. However, optical techniques are becoming increasingly popular, as evidenced by research using fixed-volume chambers in universities and R&D centers in China [21], Spain [22, 23], or by simulation studies conducted in research centers in Korea and the USA [24], and Germany and Slovenia [25].

The main factors behind an optimal operation of a compression-ignition engine are: a course of fuel injection, a quality of fuel spraying and mixing fuel droplets with air in a combustion chamber [26]. Fuel injection and spraying are the main factors that determine quality of a combustion process [27]. The injection process is responsible for a correct supply of fuel to a combustion chamber where spraying occurs, i.e. migration of fuel that leads to breaking liquid into droplets. Spraying forms a stream similar to a conical section of a sphere with drops of different size and speed. The main parameters of such a stream are as follows: an angle of spray, a range and distribution of liquid, diameters of droplets and their distribution [28]. The first two are factors behind the nature of spray, but size of droplets that determines a rate of evaporation of fuel cannot be ignored even in analyses. A popular method for evaluating the spraying process is currently an optical test that enables us to directly observe a fixed volume in an engine or chamber, which results in improved operating parameters and ecological internal combustion engines [20, 29–31].

The dynamics of fuel injection and the efficiency of a fuel system significantly affect the level of exhaust emissions, fuel consumption, ease of starting an engine, its flexibility and noise emission. For constant engine operating conditions defined by load and rotational speed of a crankshaft if fuel injection pressure and the share of recirculated exhaust gases are simultaneously increased smoke emissions can be reduced and nitrogen oxide emissions remain constant. An injection of a pilot dose can reduce noise, especially at idle or low loads and crankshaft speeds. However, an injection of a pilot dose can sometimes have an adverse effect and a compromise between nitrogen oxide and particulate emissions can be impossible. What is more, injection repeatability is difficult to control as a pilot dose decreases. Flexible dividing an injected fuel dose into several doses is demanded to control exhaust and noise emissions and regenerate an exhaust after-treatment system.

The scientific literature on the use of hydrogen in compression-ignition engines is often not comprehensive, so it is hard to claim that using this gas is reasonable and it can lead to ambiguous conclusions. Such an opinion is also confirmed in [32]. It is also focused there that the reasons for observed changes in the combustion process are not explained. The hydrogen combustion process is very interestingly presented in the paper [33]. Using a computational solver, the authors analyzed the pure hydrogen combustion as a potentially cost-effective and preferred strategy for direct injection compression ignition engines, due to its ability to achieve high heat release rates and low heat transfer losses, as well as potentially zero $CO_2$ emissions. Therefore, large-scale studies within the 6th European Union Framework Program in the HyICE project "Optimization of the Hydrogen Internal Combustion Engine" (2004-2007) have been taken as a starting point. The project aimed to optimize the design of an internal combustion engine using hydrogen as a dual fuel [34]. Numerous companies and research centers were involved in these activities. The most promising concepts of how to form a fuel-air mixture were Direct Injection and Cryogenic Port Injection (mixing cryogenic Hydrogen gas (-240 °C) with aspirated air. In both concepts, values exceeding today's petrol engines were achieved for power density (100 kW/1 $dm^3$) and efficiency (42%), although these are not the maximum ones to be achieved [35, 36].

Hydrogen is the only carbon-free fuel that does not release $CO_2$ during combustion. The "European Hydrogen & Fuel Cell Technology Platform" report by the European Commission [37] states that the use of hydrogen in internal combustion engines is a concept targeted for application in the near future as an intermediate step before the fuel cell technology is improved. The arguments supporting just like that solution are high efficiency and power density, low cost, the possibility of using two fuels at the same time during the transformation phase and high potential for a quick mass market launch. Internal combustion engines which can currently burn hydrogen besides traditional fossil fuels are based on the indirect gas injection technology, which reduces power density by about 20% compared with a supply by a liquid fuel only. The injection of hydrogen directly into the combustion chamber makes it possible to increase the power output by approximately 15 % compared with a liquid fuel supply [35]. The paper [38] points out that the performance of a compression ignition internal combustion engine can be evaluated by various parameters obtained during engine indication. These are, e.g. indicated mean effective pressure, the coefficient of variation of the standard deviation of combustion chamber pressure and the deviation of combustion chamber pressure from its mean values.

This study focuses on the analysis of the indicated mean effective pressure, the maximum pressure, the crank angle of maximum pressure and the amount of heat released during the combustion process of hydrogen and diesel fuel in a compression ignition engine. Each of these indicators influences the quality of the combustion process, which results in decreased or increased emissions.

## MATERIALS AND METHOD

Each measurement time was 10 s and was repeated three times. In total, the parameters from 375 engine cycles were analysed for all measurement points. The measurement was started after stabilisation of the set parameters following a change in fuel dose, torque or hydrogen injection angle. The measurements were taken at 1500 rpm in the conditions of an engine dynamometer.

Combustion was carried out for five different hydrogen doses (H0-H4), four fixed initial torques (T1-T4) and two start angles of hydrogen injection directly into the combustion chamber (E/L). The changed gaseous fuel injection start angles were defined as early and late angles, which is 40° after TDC (E symbol) and 160° after TDC, (L symbol) direct injection, respectively. The injection start angle was experimentally determined to achieve the maximum time and volume of hydrogen injection for the given test facility.

The injection of hydrogen is done directly into the combustion chamber with four separate injectors. This solution has been presented in detail in the work [10]. Fig. 1 shows the measuring points.

The test bench is located in the Laboratory for Innovation, Transfer and Monitoring of Development of Technologies of Alternative Propulsions in the Centre for Innovation and Advanced Technologies of the Lublin University of Technology (Poland). The research object is an ADCR engine with a displacement of 2,636 $cm^3$. The engine is equipped with a diesel and compressed hydrogen supply systems. The research were conducted on a test stand, see Fig. 2 and Fig. 3.

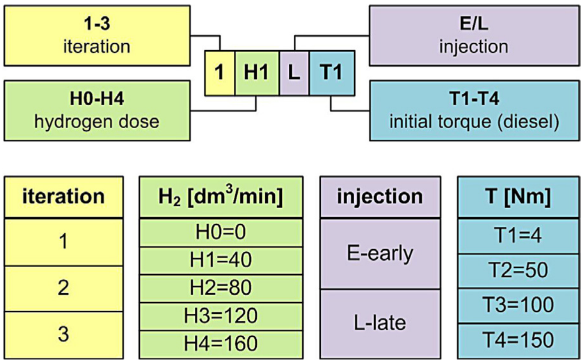
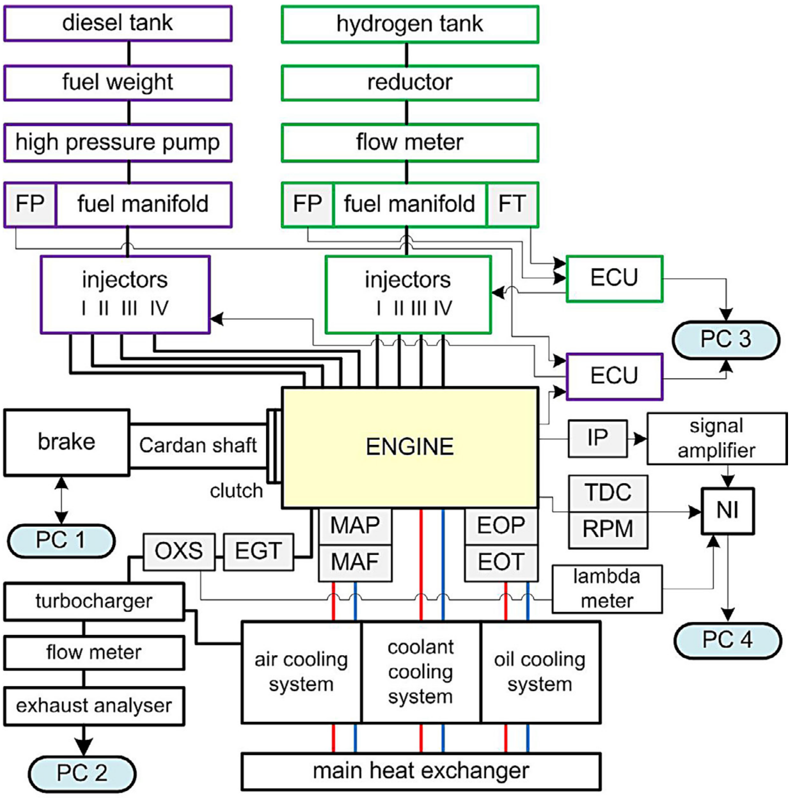


**Fig. 1.** Measuring points



FP – fuel pressure sensor; FT – fuel temperature sensor; ECU – dedicated and original engine controller; NI – National Instruments; PC1-PC4 – computer units for individual systems; IP – indicator pressure sensor; TDC – crankshaft position sensor; RPM – rotation speed sensor; OP – oil pressure sensor; OT – oil temperature sensor; MAP – manifold absolute pressure sensor; MAF – mass airflow sensor; OXS – lambda sensor; EGT – exhaust gas temperature sensor

**Fig. 2.** Diagram of the dynamometer stand

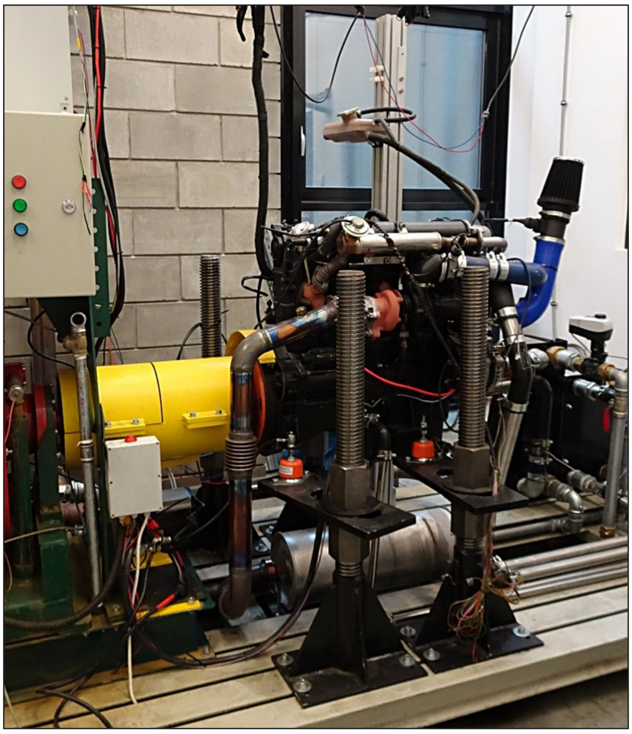


**Fig. 3.** Test bench

## RESULTS AND DISCUSSION

The results were plotted for three repetitions, for the single cylinder in box-and-whisker diagrams. The effect of changing the hydrogen injection start angle on selected engine operating parameters was compared. Fig. 4 illustrates the indicated mean effective pressure, standard error and standard deviation. An increase in the standard deviation can be observed for extreme loads.

Fig. 5 compiles the obtained values of the indicated mean effective pressure, depending on the applied hydrogen dose, torque, and gaseous fuel injection start angle. Increasing the hydrogen dose results in an increase in the IMEP by about 0.1 MPa per successive increase in hydrogen flow by 40 dm³/min. This is related to the higher fuel dose supplied during the combustion process. This trend is very clear for the medium loads (T2, T3). The growth dynamics for the highest torque is slightly

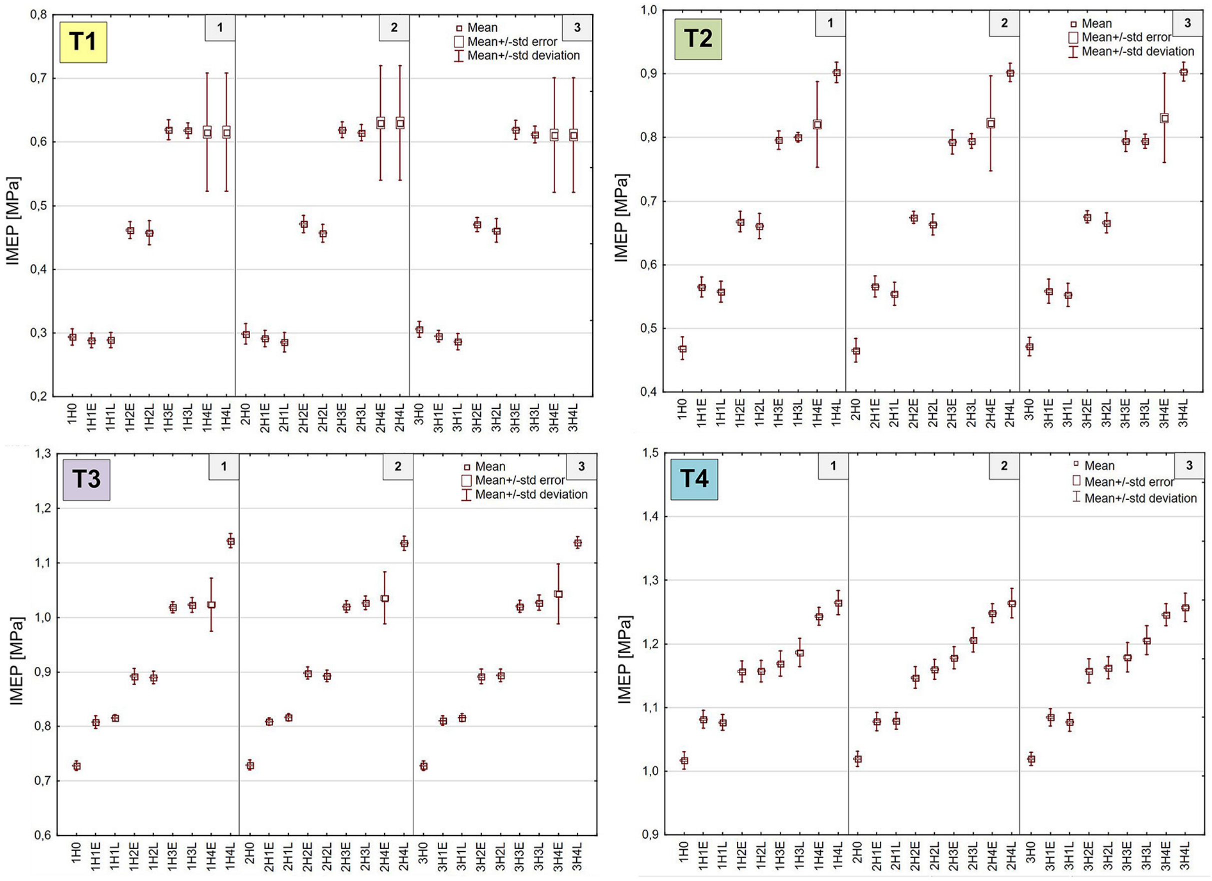


**Fig. 4.** Indicated mean effective pressure at T1-T4 torques

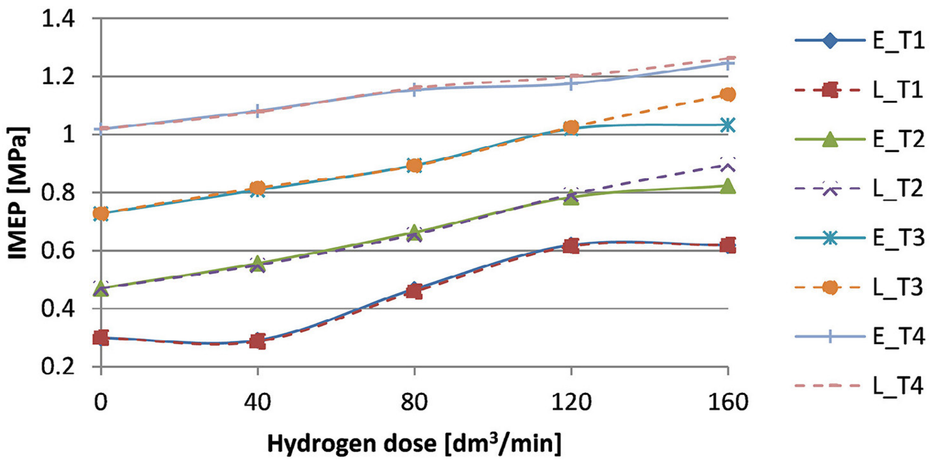


**Fig. 5**. Indicated mean effective pressure at the analyzed measurement points as a function of the hydrogen dose

lower, while for idle it occurs in a limited range. Neither the first hydrogen dose, nor the last one at the lowest load caused a change in the IMEP. This suggests a rapid diffusion of fuel in the combustion chamber. The differences between early and late injection only become visible at high hydrogen doses and higher torques. A higher IMEP can be observed for the late injection. This is due to the harmful rumble in the combustion chamber. This rumbling could by caused by a too rich fuel mixture and a rapid acceleration of the flame front. Due to the large amount of hydrogen and small of diesel, the temperature may have been too high.

Figure 6 shows the obtained values of the maximum cylinder pressure at the particular measurement points. The results are given for three repetitions. The presented values include the maximum pressure, standard error and standard deviation. In the case of extreme loads, similarly as for the

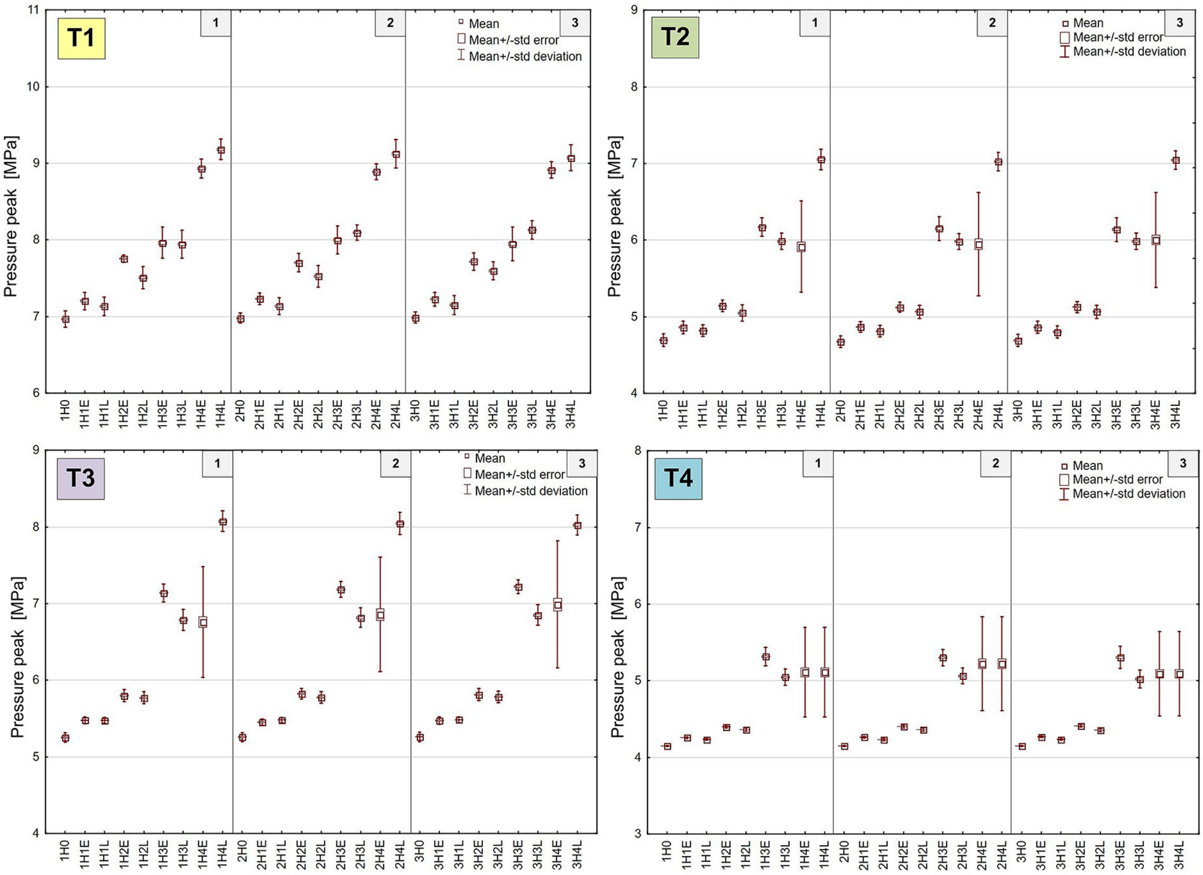


**Fig. 6.** Maximum pressure for T1-T4 torques

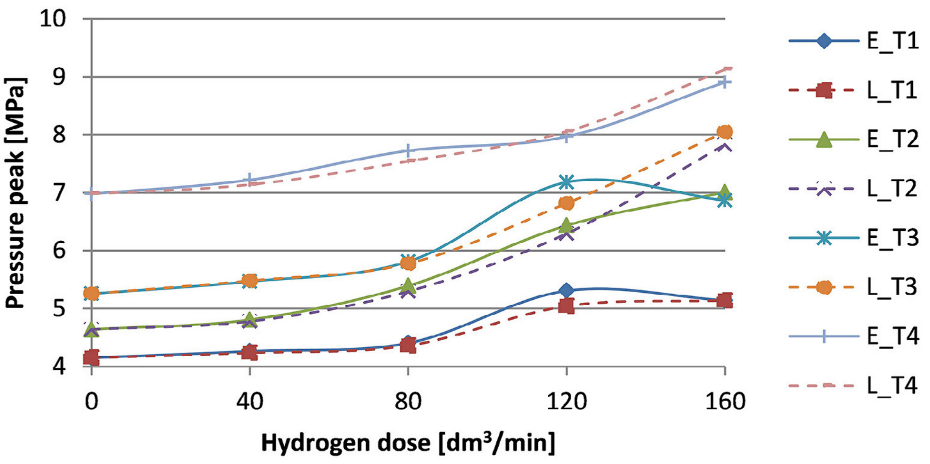


**Fig. 7.** Maximum pressure at the analyzed measurement points versus the hydrogen dose

indicated mean effective pressure, the increase of the standard deviation can be observed.

Figure 7 summarizes the maximum pressure values obtained, depending on the amount of hydrogen supplied to the engine. Usually, as the hydrogen dose increases, the maximum pressure in the cylinder also increases. This indicates the correct combustion process. For the lowest hydrogen dose (H1) for 3 out of 4 analyzed loads, there are no differences in the value of the maximum pressure when the injection start angle is changed. At the highest load (T4), a slightly higher pressure occurs with early injection for hydrogen doses H1 and H2, while the situation is reversed for higher hydrogen doses (H3, H4). It should be noted here that the maximum applied hydrogen dose was determined experimentally before the occurence of rumbling or at its boundary, which may have influenced the value of pressure.

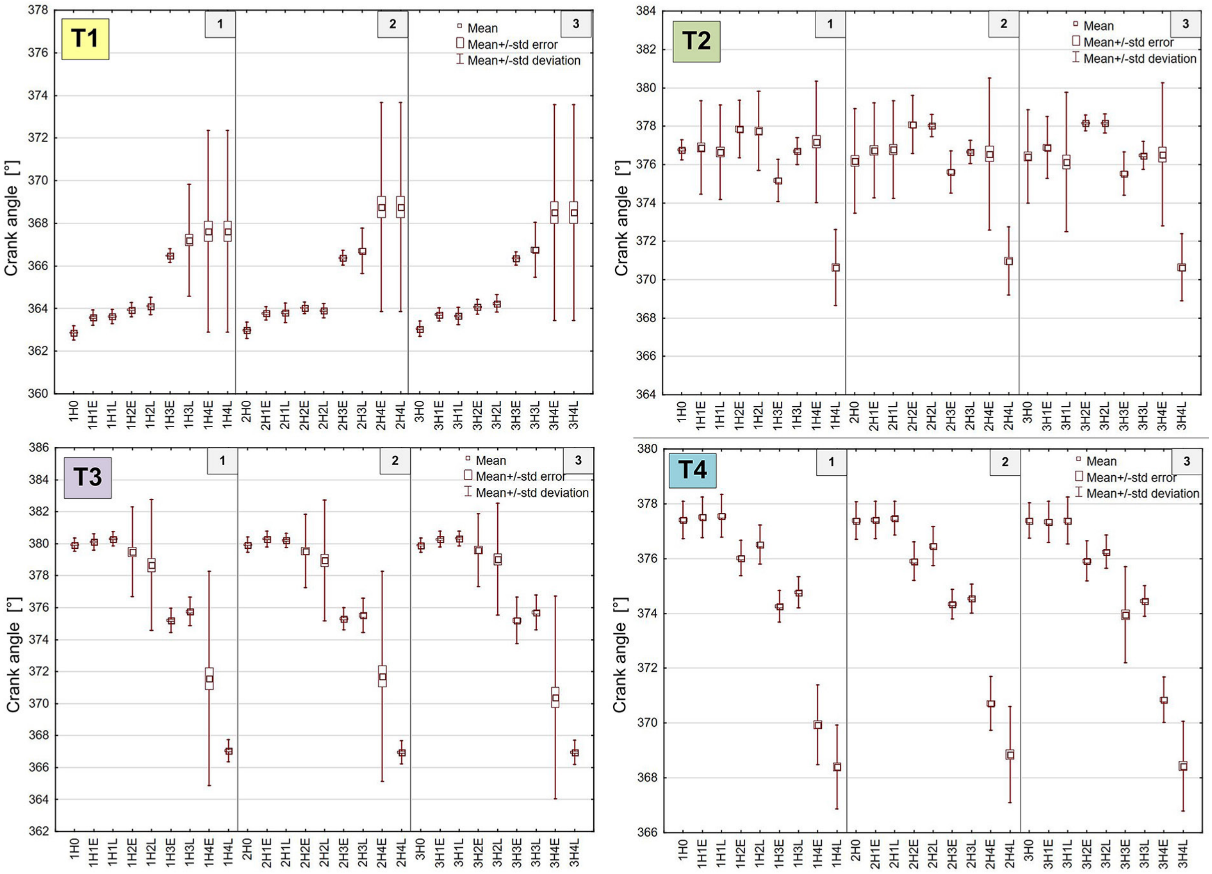


**Fig. 8.** Crank angle of maximum pressure for T1-T4 torques

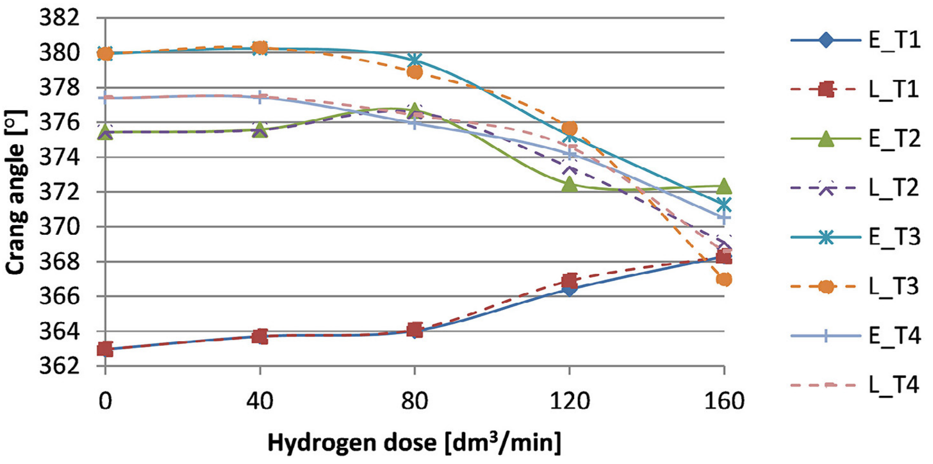


**Fig. 9.** Crank angle of maximum pressure at the analyzed measurement points versus the hydrogen dose

Figure 8 shows the obtained values of the crank angle of maximum pressure in the cylinders at each measurement point. The results are presented for three repetitions. The presented values are the crank angle of maximum pressure, standard error and standard deviation.

Figure 9 shows the occurrence of the crank angle of maximum cylinder pressure. If this angle at idle increases with increasing a hydrogen dose, it decreases in other cases, regardless of the gaseous fuel injection start angle. It is worth noting that the lowest applied hydrogen dose (H1) did not actually affect the occurrence of the angle of maximum pressure. Earlier injection for hydrogen dose H3 resulted in earlier peak pressure, while for hydrogen dose H4 the opposite was true in all analyzed cases.

Figure 10 shows the obtained values of heat released at the particular measurement points. In the case of extreme loads, as for the analyzed

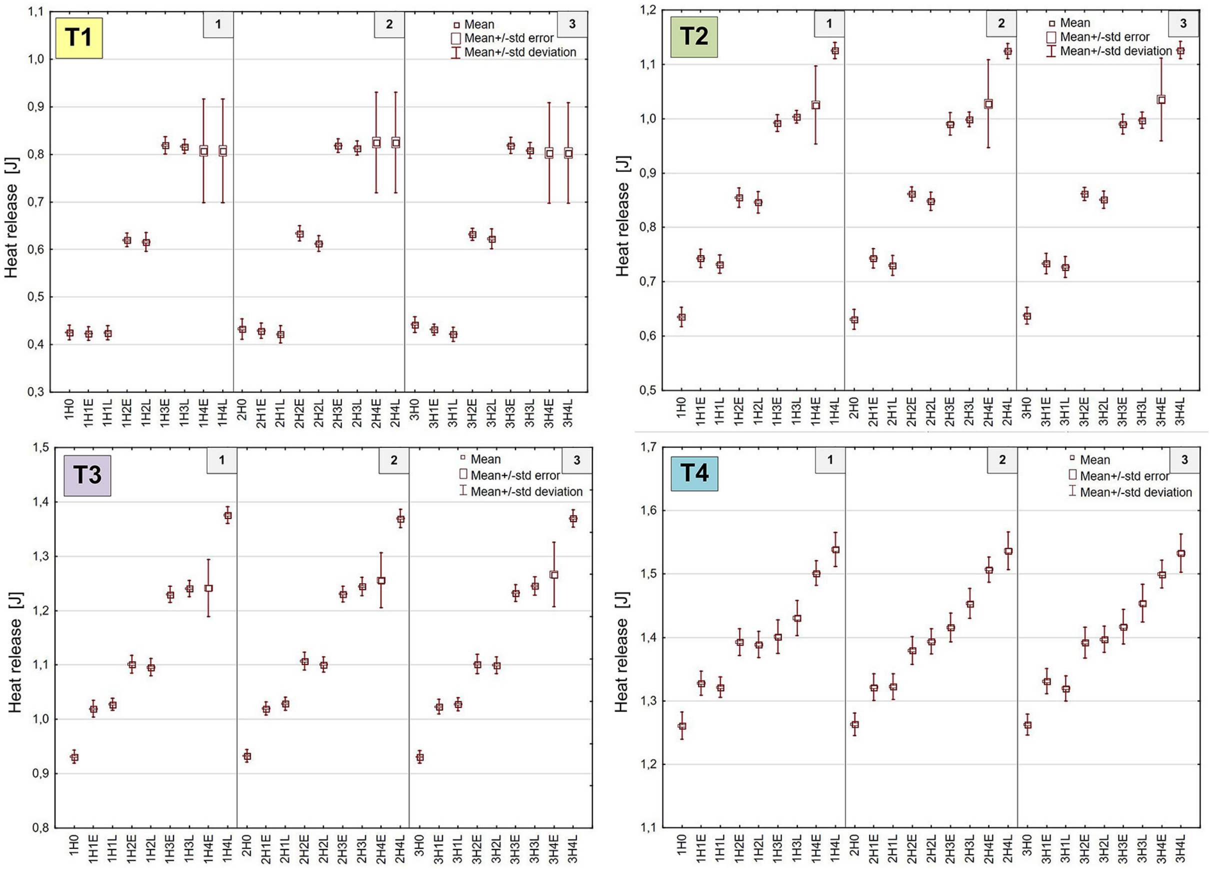


**Fig. 10.** Heat release for T1-T4 torques

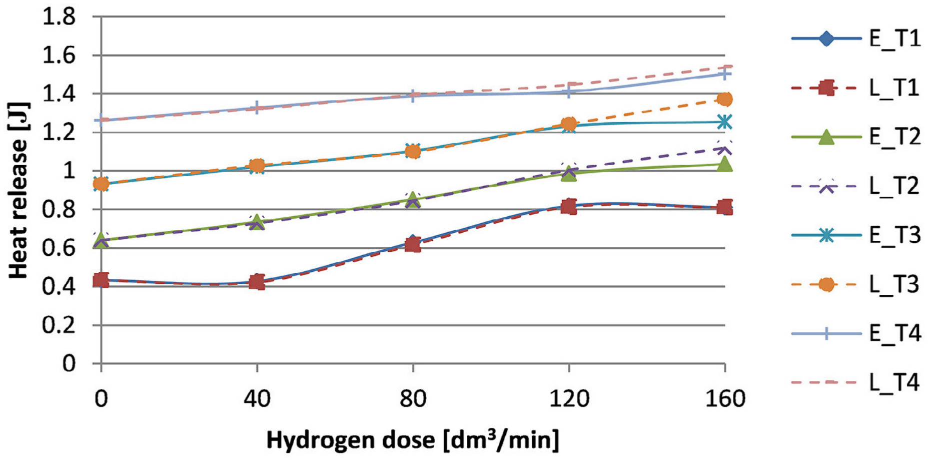


**Fig. 11.** The heat released at the analyzed measurement points as a function of the hydrogen dose

pressure values, an increase in the standard deviation can be observed. In the case of idling (T1), no increase in heat release was observed for the lowest and highest hydrogen doses (H1, H4). No increase in heat release accompanied by no increase in mean effective indicated pressure means an incorrect combustion process. At the selected measurement points, adding or increasing the hydrogen dose did not improve the engine performance, and the supplied gas probably was not burnt.

Figure 11 shows the values of the heat released during the combustion process of diesel fuel and hydrogen. Usually, as the load and hydrogen doses increased, the amount of heat also increased. For early injection and for the maximum hydrogen doses applied, the amount of heat released was lower than for late injection, which may mean that the supplied fuel was not completely burnt.

## ANALYSIS

The conducted analysis focused on determining whether there are significant differences between early and late injection and how these changes affect the measured parameters. For this purpose, three-dimensional surface plots were made for each of the analyzed combustion parameters using the

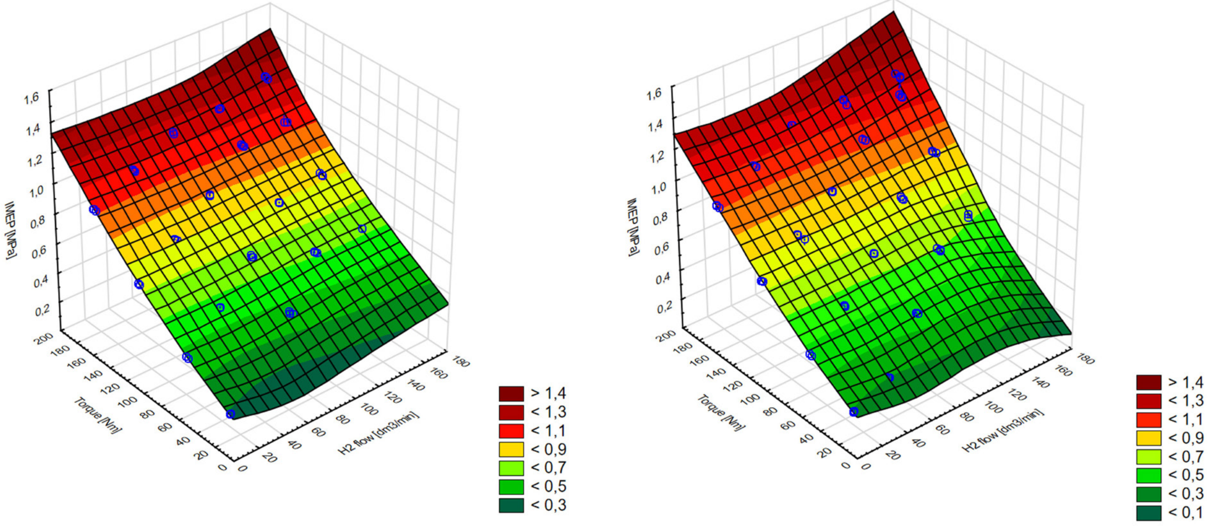


**Fig. 12.** The indicated mean effective pressure as a function of the torque and hydrogen dose for early (left) and late (right) injection

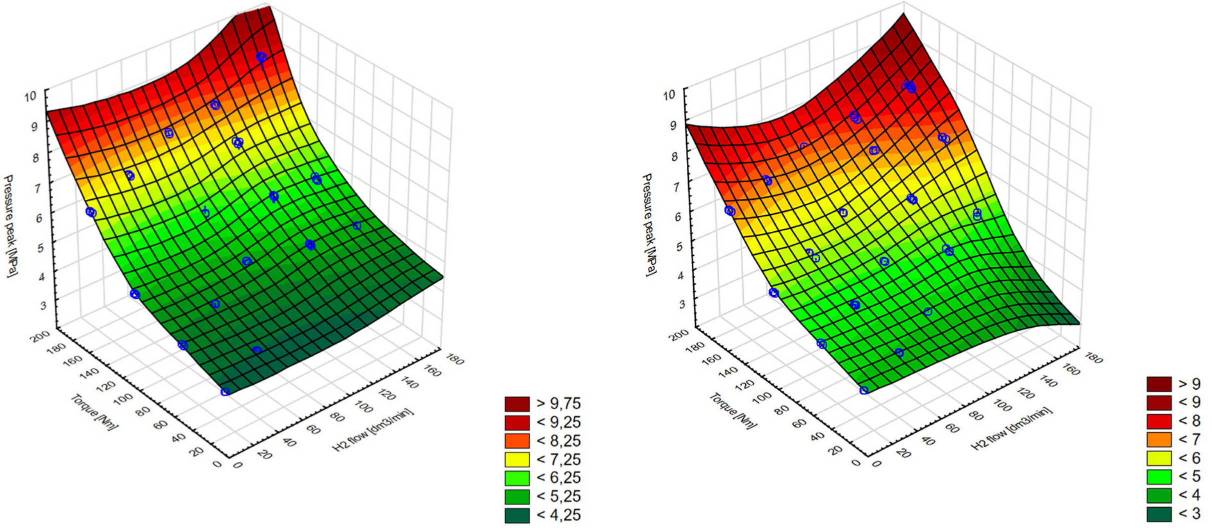


**Fig. 13.** The maximum pressure as a function of the torque and hydrogen dose for early (left) and late (right) injection

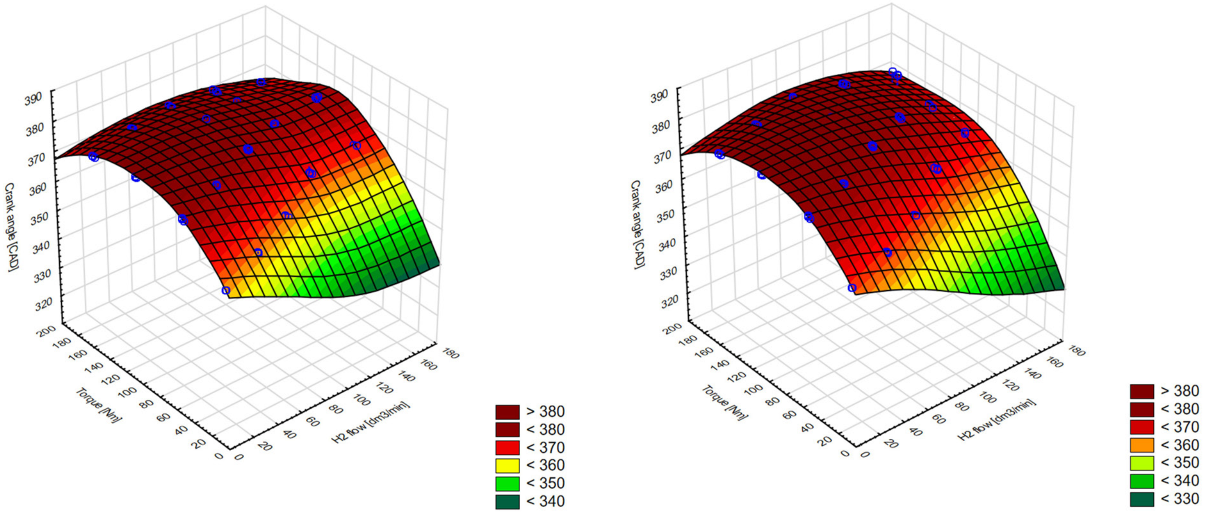


**Fig. 14.** The angle of maximum pressure as a function of the torque and hydrogen dose for early (left) and late (right) injection

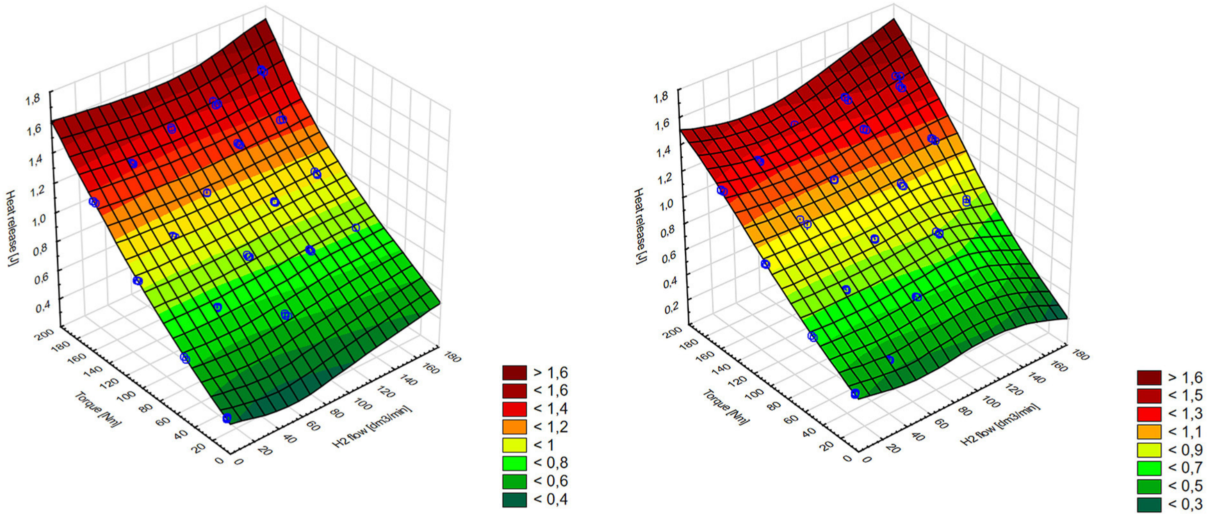


**Fig. 15.** The heat released as a function of the torque and hydrogen dose for early (left) and late (right) injection

Statistica NKWO software function of "distance-weighted least squares smoothing". Depending on the torque recorded and the amount of hydrogen, the results were presented for the indicated mean effective pressure (Fig. 12), the maximum pressure (Fig. 13), the angle of its occurrence (Fig. 14) and the heat released (Fig. 15).

In the next step, the significance of the differences shown in the visualizations was checked. For this purpose, a t-Student test analysis was performed and the significance of differences between the complete groups of the analyzed parameters for early and late injection was determined. The zero hypothesis of the absence of significant differences between the groups was put forward as:

$$H_0: \beta_i = \beta_i^* \tag{1}$$

and alternative (there are differences between the groups):

$$H_1: \beta_i \neq \beta_i \tag{2}$$

A significance level of $\alpha = 0.05$ was chosen. For the significance level indicated, the border value of $t_\alpha = 2.0003$. The results are presented in Table 1.

It was concluded from the Student's t-distribution tables that the results of the analysis are not

**Table 1.** Parameter t for the measured points

| All measured points | *t* |
|---|---|
| IMEP E vs. IMEP L | -0.192 |
| Pressure peak E vs. Pressure peak L | 0.180 |
| Crank angle E vs. Crank angle L | 0.065 |
| Heat release E vs. Heat release L | 0.011 |

**Table 2.** Parameter t for the H4T3 measurement point

| H4T3 point | *t* |
|---|---|
| IMEP E vs. IMEP L | -34.274 |
| Pressure peak E vs. Pressure peak L | -26.138 |
| Crank angle E vs. Crank angle L | 11.1365 |
| Heat release E vs. Heat release L | -35.209 |

within the critical area, because $t_i < t_\alpha$ for all analyzed parameters. According to the study, there are no significant differences between the analyzed groups so for the significance level α = 0.05, there are no grounds to reject the zero hypothesis $H_0$ in favor of the alternative hypothesis $H_1$.

A Student's t-test analysis was also performed for the selected measurement points where the differences were evident even without statistical analysis.

The analysis was performed at H4T3 for 300 recorded samples, 100 in each iteration. The results of the t-test analysis are presented in Table 2.

From the Student's t-distribution tables, it is clear that the results of the analysis are within the critical area, because $t_i > t_\alpha = 1.9679$. According to the analysis, there are significant differences between the investigated groups so for the significance level α = 0.05, there are grounds to reject the zero hypothesis $H_0$ in favor of the alternative hypothesis $H_1$.

## CONCLUSIONS

The following conclusions can be drawn from the conducted research and analysis. Higher indicated mean effective pressure occurs for the later gaseous fuel injection start angle if the maximum hydrogen doses applied. Maximum pressure and the angle of its occurrence in the analyzed measurement points depend on the gaseous fuel injection start angle and the hydrogen dose. The nature of this dependence requires a more detailed analysis. The amount of heat released is related to the quality of the combustion process. No increase of heat release after increasing the fuel dose and changing injection parameters can inform about incorrect combustion. In the assumed experimental plan, the statistical analysis performed globally for all measurement points shows that there are no significant differences for the significance level α = 0.05 between early and late hydrogen injection. The analysis was performed using a Student's t-test. The adopted significance level of α = 0.05 is characteristic for technical sciences. The obtained results concern the values of indicated mean effective pressure, maximum pressure, angle of its occurrence and heat release for different points of hydrogen injection into the combustion chamber.

5) Important differences for the significance level α = 0.05 between early and late hydrogen injection are clear if the selected measurement points, especially for extreme loads are separately analyzed. The obtained results are related to the values of indicated mean effective pressure, maximum pressure, angle of its occurrence and the heat release for different points of hydrogen injection into the combustion chamber. Relatively large standard deviations for some measurement points suggest an unstable combustion process. This was most often the case with extreme engine loads and large hydrogen doses. As the load and the amount of hydrogen increased, the non-repeatability of the working process increased. The increase in diesel dosage seems to allow a higher percentage of hydrogen to be delivered without an adverse impact on the working process. This means that at higher diesel doses, more hydrogen can be delivered by percentage.

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